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16. ABSTRACT

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An Analogue Echogram Range Gate Tracker for Clinical Echocardiography*

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The fundamental purpose of this paper is to present the results of a feasibility study for an on-line, real-time automatic range gate tracker (ARGT) for clinical echocardiography, specifically for the purpose of determining cardiac output noninvasively and in real time. The basic ARGT design represents an implementation of specific algorithms and a system controller that permit user interaction and interpretation of clinical echocardiograms. In its analytical mode, the ARGT automatically tracks cardiac echoes as visually perceived and selected by the user. While tracking specific cardiac echoes, the ARGT converts the complex ultrasonic echogram into a pair of meaningful analogue signals (corresponding to the motion of the anterior and posterior left ventricular walls) from which dimensional information corresponding to dynamic geometric changes of the heart are derived. From this information, the cardiac output is computed in real time.

INTRODUCTION

The assessment of adverse cardiac health effects in human subjects resulting from environmental pollutant exposures has been difficult to quantitate due to the subtle nature of the intrinsic physiologic compensatory mechanisms. Noninvasive techniques and procedures to characterize the dynamic performance of the myocardium before and after exposure to environmental pollutants has been an essential component in the detection and assessment of the subtle compensatory changes that occur in the cardiovascular system.[1,3,10] The technique of echocardiography has been es-

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tablished as a noninvasive procedure for the evaluation of certain pathophysiological cardiovascular conditions particularly in environmental medicine.

Characteristically, evaluation of cardiac performance by echocardiograms has been accomplished by manual (graphic) methods and has been well documented.[4,9,11] Validation of cardiac performance utilizing analytical echocardiography has also been well confirmed through the use of simultaneous angiographic procedures.[5] However, a major limitation in analytical echocardiography appears to be (a) the time required to process strip chart recordings, (b) the manual computation of cardiac performance parameters, and (c) the quantitative evaluation of the echogram in a rapid, convenient, and reliable fashion. These limitations may be overcome with a real-time on-line "intelligent" analytical echocardiographic processing system.

Computer-assisted analysis of echocardiograms has been attempted in many ways. The recent advances in analytical echocardiography have involved extensive development in hardware design and software implementation resulting in limited clinical applicability.[6,7,8] As a consequence, an analytical echocardiographic processing system has been designed, developed, and implemented for the specific purpose of assessing the adverse consequence of environmental pollutant exposure on cardiac performance. It is the purpose of this paper to describe this system in terms of its design and rationale and to present the results of the feasibility study in terms of an on-line, real-time application for human echocardiography, specifically for the purpose of determining cardiac output noninvasively and in real time.

SYSTEM DESCRIPTION

The fundamental basis for the system described in this paper has been adopted from a highly selective video echo-detection process frequently called (in radar terms) *range gate processing*. Utilization of radar-like range-gating techniques permits a high degree of selectivity in tracking only those echo signals of interest. Conventional radar range-gating techniques have enjoyed only limited application in clinical cardiology mainly because of the unacceptable phase shifts produced by the system electronics, i.e., low-pass filters. Recently, several systems have been successfully developed to manually track the motion of the ventricular myocardium and estimate cardiac output in human subjects.[2,7,8] However, each of these systems was limited in its ability to maintain tracking without loss of signal and to compute cardiac output automatically and in real time.

Recently, however, efforts have been successful in maintaining the tracking function for extended periods of time with a reasonable degree of confidence.[6] This most current design incorporates the capability of an automatic range gate tracker and the simultaneous computation of cardiac output. The tracking system in its comprehensive form is referred to here as the Automatic Range Gate Tracker (ARGT). It is the fundamental objective of the ARGT to emulate, through implementation of software and a microcomputer, the ability to visually perceive, track, interpret, compute, and analyze an echocardiogram in real time. This system is dependent in part upon operator–machine interaction to set up the echogram, identify cardiac echoes to be evaluated, and initiate the analytical procedures (implemented on a microcomputer) based on sound scientific judgment.

The ARGT is based on a modified commercial echocardiograph (Smith Kline SKI-20) operating with a pulse-repetition frequency (PRF) of 1,000 Hz exciting a 2.25-MHz transmit/receive piezoelectric hand-held transducer. The echograph has been modified to interface with a video-preprocessing circuit for processing A-mode echo signals (Figure 1 echoscope) in the form of an envelope detector in series with an analogue-to-digital converter (ADC) (Figure 2). This processed signal is then interfaced with an M-6800 Exorcisor (Motorola Inc.) microcomputer. The M-6800 is supplied with a 32K RAM/ROM and four I/O ports supported by a *modified architecture* for automatically tracking video echoes.

Functionally, two range gates are utilized to select (simultaneously and in real time) the anterior (near) and posterior (far) left ventricular wall ultrasonic echoes viewed in the A-mode or M-mode of the echocardiograph. Initially, these cardiac echo signals are selected manually by positioning cursors corresponding to the center of the near/far range (depth) gates (in the A-mode) in the vicinity of the echo boundary to be tracked. Each cursor is controlled by a potentiometer, which the operator may manipulate and which provides a *z*-axis intensity-modulated cursor signal for display and verification of the cursor position (depth). These signals function as range gate "pointers" and are superimposed on the A-mode cathode ray tube display lower left (Figure 1). Once the echo to be tracked has been selected with the cursor, the processor is synchronized with the 1,000-Hz PRF of the ultrasonic transducer, and then followed by analogue-to-digital (ADC) sampling and digitizing of the DC voltage of each cursor control potentiometer. This process converts the cursor positions

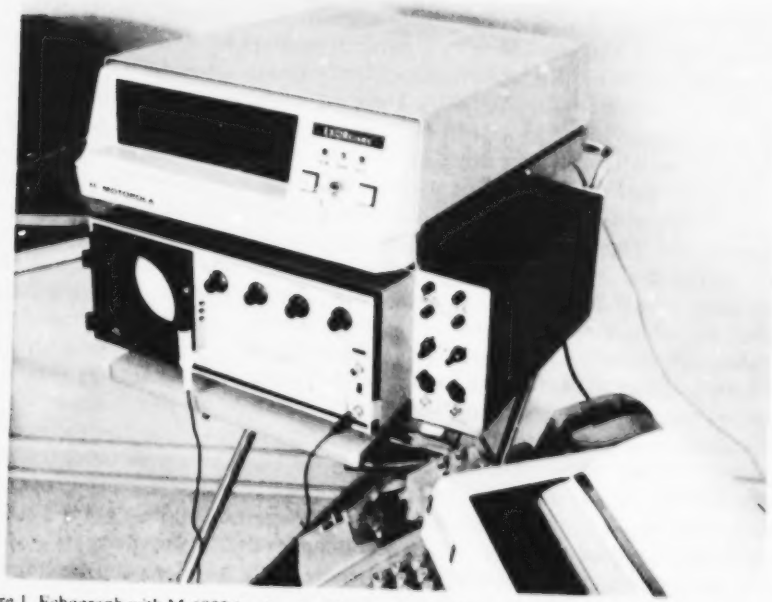

Figure 1. Echograph with M-6800 (top), manual range gate tracker outboard mounting and keyboard console in foreground.

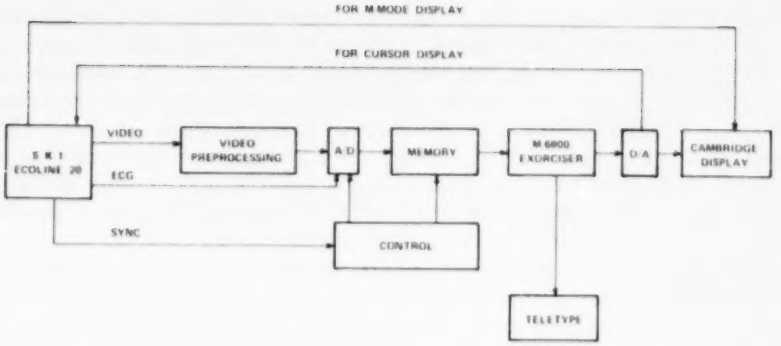

Figure 2. Automated echocardiograph processing system block diagram.

(near/far) into a digital value, which in turn is stored in the microcomputer for subsequent processing.

The digitized values of the near and far cursor potentiometers provide the (software) reference for the starting address or the initial tracking position for each echo. Simultaneously, the ultrasonic video echo signals are preprocessed through a half-wave rectifier and envelope detector. This procedure reduces the complex video image into (two) simple envelope signals, which represent the motion of the wall boundaries being tracked. This envelope is then digitized (analogue-to-digital converted) at a sampling rate of 1 MHz. Each return echo signal contains the depth information of approximately 15 cm from the chest wall. The onset of the ultrasonic transmit pulse initiates a software sampling period of 1,000 microseconds (depth period) constituting one data set of echo returns. The sample coding for this period establishes a 128 μs maximum range gate width based on a count size of (6 bits). The respective gate widths are developed by the count sample (1 count = 1 μs) giving 64 or 128 μsec maximum gate widths. The inter-gate period of 20 μs is a minimum period that is desirable since the second gate is (serially) initialized at the completion of the first gate. By utilizing range gate techniques, the video peaks develop gate widths averaging 20 μs (15.4 mm), providing a minimal resolution to establish a digital envelope profile of the echo within each respective range gate. This technique reduces the need to digitize the signals corresponding to the full depth range of 15 cm, thereby substantially reducing the memory storage requirements to less than 4K of RAM for this function.

The above range gate design emulates the TTL circuit logic of the dual range gate and tracking features employed in an earlier study.[6,7,8] The echo signals being tracked represent data (to the M-6800 input ports) through two potentiometers. The cursors locate the echo signals to be tracked and serve as the starting address for the initial tracking function. Hence, the initial cursor position information and the near/far cardiac echo information are each stored into respective RAM locations that function as a pair of continuous circulating range gate memory buffers.

Since each cardiac echo moves (in real time) as a result of cardiac pumping ac-

tion, the digitized samples of the position envelope reflect this change within each range gate. After the position envelope is sampled and stored in memory, a subroutine is called to perform a binary peak detection (software comparator) procedure on the digital values within each range gate. Essentially, this procedure selects the peak value within each range gate and centers it around the echo being tracked. This procedure is performed for each of two echo signals within each range gate each time the transducer fires (i.e., 1,000 μsec). For each subsequent transducer burst, the tracking process positions each range gate centering around the newly detected peak. The net effect of this process is a nearly continuous time history (once every ms) of the position of each boundary being tracked.

As the boundary position changes, the peak value is updated and digitally compared to the peak value from the previous cardiac cycle. Significant differences in peak values from the previous cardiac cycle cause the range gate position to automatically recenter itself around the new peak. In this manner, tracking is accomplished for a changing echo and a new center position is established for each range gate. This process occurs simultaneously for the near and far wall range gates. Updating the new and changing values of the tracking gates occur by rewriting over previous (cardiac cycle) digital peak values in each circulating range gate memory buffer.

The emulated range gate software also updates the new gate positions on the A-mode display so as to cause each gate to *move in real time* as it tracks the changing echo positions. Since it is desired to automatically position each range gate over the center of the respective echoes, differences in the previous (as opposed to the current peak digital values) cause an interrupt of the range gate algorithm and update the range gate positions over the echoes of interest. While in the track mode, the cursors (z-modulated) "follow" the video signals being tracked and are displayed in both A- and M-modes for visual inspection and confirmation.

The full depth range of the position envelope (15 to 20 cm) is not digitized. Only the echo signals within each (near and far) range gate are sampled and stored into memory. All other echoes are eliminated by the range gate selectivity whose width is variable as a function of the returning video echo width and peak. This procedure significantly reduces memory requirements for the tracking function and processor time for the implementation of cardiac output measurements performed by the microcomputer.

FEASIBILITY STUDY RESULTS

The feasibility studies associated with the evaluation of the design of the ARGT system were performed in two phases: Initially, studies were performed on a mechanical model of the heart that consisted of a pump-driven water-filled bladder system. Upon the successful completion of these studies, the ARGT system was evaluated on human subjects. Neither of these studies was intended to be complete or conclusive by itself. Rather, the intent was to demonstrate that (a) the ARGT system could indeed track the boundary motion of two cardiac structures simultaneously (specifically, the anterior and posterior left ventricular wall), (b) useful information regarding the continuously changing dimensions of the heart can be collected nonin-

vasively with ultrasound, and (c) the dimensional information may be utilized to compute an index of cardiac performance, specifically cardiac output.

Tracking validation studies were performed using a mechanical heart model to evaluate the software tracking reliability of the ARGT system. The model was composed of a motor-driven rubber bladder immersed in saline. This configuration provided artificial anterior and posterior wall boundaries from which echoes could be beamed and measurements taken. A pulse (to simulate the ECG) is generated from a magnetic reed switch closure driven by an offset cam linked to the bladder. A representative echogram of the heart model being processed with the ARGT system shows the tracking function (Figure 3). The anterior wall signal represents the raw digital-to-analogue converter (DAC) output from the microcomputer. The posterior wall DAC signal output was passed through a low-pass filter before it was displayed. In this illustration, the analogue signals corresponding to the real-time wall motion are superimposed on the echogram of the saline-bladder mechanical model.

A left ventricular echocardiogram taken from a normal human test subject during the tracking procedure is shown in Figure 4. In this illustration the mitral valve is identified as an anatomic reference position from which the tracking function begins. The two straight (horizontal) lines to the right of the mitral valve illustration represent the period during which the M-6800 microcomputer is first computing range gate positional information. Following this computation period, a conventional left ventricular echocardiogram is seen, including a portion of the right ventricle, the ventricular septum, the LV walls, the chordae, and the posterior LV wall. The DAC output of the near and far ARGT is presented as an analogue signal for each wall (anterior and posterior ventricular) being tracked. The quality of the ARGT tracking signals is based on the equality of phase and amplitude relationships between two analogue signals and the conventional M-mode echogram. Figure 5 illustrates the echo tracking system (ETS) output on a different subject. The anatomic landmarks (pericardium, epicardium, and endocardium are all visible) are more enhanced and tracking reliability is improved through additional gray scale enhancement and digital smoothing of the DAC analogue output signals. The net effect of this procedure is equivalent to a hand-drawn pencil outline of the blood–tissue interface of an echogram. The ARGT system performs this procedure automatically. It is through this process that the ARGT system, with the assistance of human judgment, can detect, perceive, and track the motion of cardiac structures in an on-line real-time mode.

Once the ARGT system is tracking with some degree of reliability (as confirmed by visual verification (Figures 4 and 5)), noninvasive estimation of cardiac performance (particularly cardiac output) can be achieved. Dynamic changes of the intact heart can be assessed in terms of its instantaneous positional geometry. The algorithm for determining changing ventricular volume is given as:

Left Ventricular Volume Calculations

$$ESV = 47\ [ESD\ (CM)]^3 - 120 — MI \quad (1)$$

$$EDV = 59\ [EDD\ (CM)]^3 - 153 — MI \quad (2)$$

$$D' = \frac{7.0}{2.4 + D} \quad (3)$$

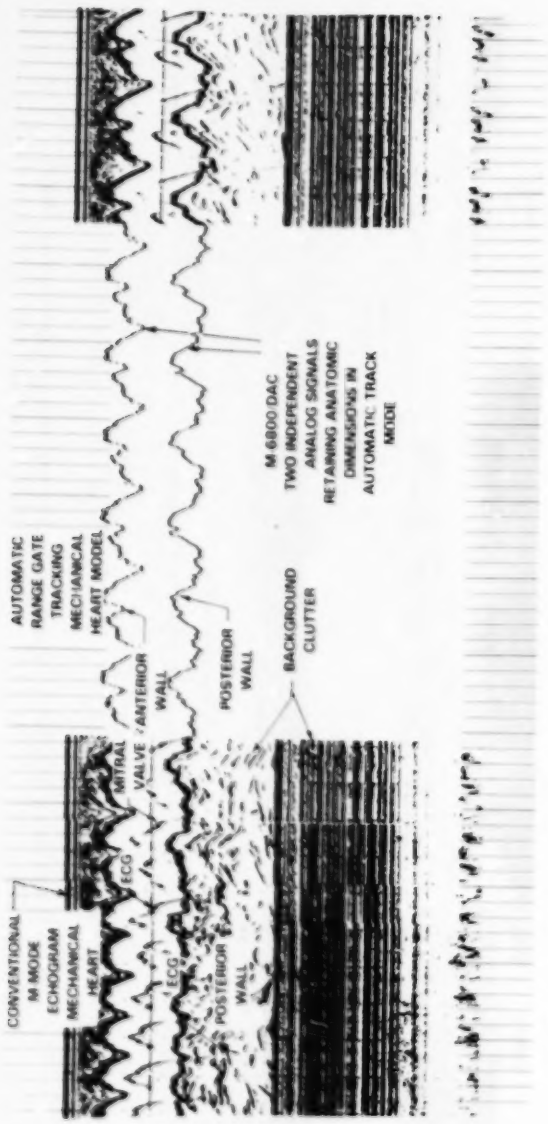

Figure 3. Echogram of heart model illustrating continuous and simultaneous near/far wall analogue tracking.

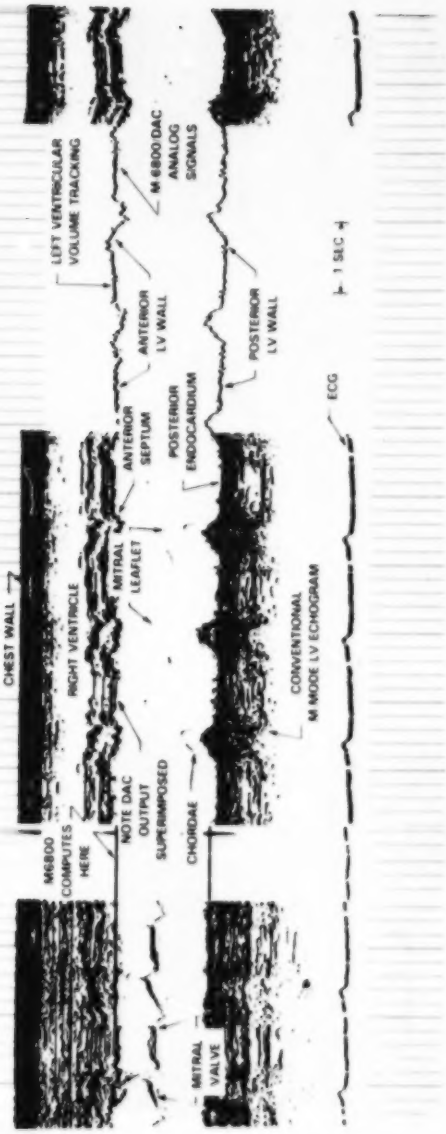

Figure 4. Left ventricular echogram of human subject illustrating anterior and posterior wall tracking.

Figure 5. Echo tracking system (ETS) of human test subject with gray scale enhancement.

$$SV = EDV - ESV \text{ (Stroke Volume)} \quad (4)$$

$$EF = \frac{SV}{EDV} \text{ (Ejection Fraction)} \quad (5)$$

$$\text{Cardiac CO} = SV(\text{ML/beat}) \times \text{H.R. (beats/1/min)} \quad (6)$$

This relationship is based on the changing of the minor axis of a prolate ellipse and has been documented adequately in the literature.[4,5] If the dimensional information obtained from the ARGT system is applied to equations (1–6), an estimate of cardiac output can be obtained.

CONCLUSION

A real-time automatic range gate tracking (ARGT) system for cardiac structures implemented by a microcomputer has been developed. Through the resources of the M-6800, large-scale integration (LSI) circuitry, and software engineering techniques, it has been possible to perform real-time tracking and estimates of cardiac performance automatically. The fundamental design was to emulate, within specific limits, the factors that affect the evaluation of cardiac performance. Specifically, the factors include visual perception, tracking, interaction, computation, and analysis of a real-time echogram. The significance of this development is in the reduction of a complex video image into simple analogue signals. The conversion of ultrasonic cardiac images to the classic analogue cardiac wave forms permits facility with echocardiographic measurements such as ventricular wall motion to a level approaching invasive cardiac catheterization techniques. The availability of near and far wave forms by this process in concert with the computational power of the microcomputer may have a significant impact in characterizing cardiac performance, patient diagnosis, and health effects research.

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BIOGRAPHIES

Mathew L. Petrovick is currently a research biomedical engineer for the U.S. Environmental Protection Agency, Health Effects Research Laboratory, Clinical Studies Division. He is responsible for the design and development of microcomputer-based cardiovascular instrumentation in support of health effects research. Previously, he was director of the Biomedical Engineering Division of the Becton/Dickinson Corporation Research Center, Raleigh, North Carolina, and responsible for artificial organ research and development (1969–1971). He has actively assisted in design and teaching graduate microcomputer curriculum (1977–1979) at

the University of North Carolina Biomedical Engineering and Mathematics Department. His 39 publications cover a broad spectrum of disciplines including biomedical engineering, medicine, criminology, aerospace, and renewable energy and fuel cell systems. He established the first (NIGMS) funded biomedical engineering laboratory at Northwestern University Medical School, Chicago, Illinois, where he served as its director from 1959 to 1969. Mr. Petrovick received his B.S.E.E. in 1952 from the American Institute of Engineering and Technology, followed by graduate studies in neurophysiology at Northwestern University Medical School (1959–1961).

Dr. George S. Malindzak, Jr., professor and chairman, Department of Physiology, Northeastern Ohio Universities College of Medicine, was born January 3, 1933, in Cleveland, Ohio. He received his A.B. (cum laude) degree from Western Reserve University in 1956, and his M.S. and Ph.D. degrees from Ohio State University in 1958 and 1961, respectively. He held faculty positions in the Department of Physiology at Ohio State University, Bowman-Gray School of Medicine, University of North Carolina, and Northeastern Ohio Universities College of Medicine. Dr. Malindzak's major research interests are in the areas of cardiovascular physiology, particularly regulation of coronary blood flow, echocardiography, and coronary vasospasm. He has had extensive training and experience in the biomedical engineering aspects of physiology and digital computer applications to physiological problems. Postgraduate training includes Artificial Intelligence, Rand Corporation, 1962; Digital Computer Engineer (MIT) 1963; Electrical Engineering, Stanford University, 1969. He currently holds an adjunct appointment as professor of Electrical Engineering, University of Akron, Electrical Engineering Department. He is or has been a member of 13 professional societies, including the Biomedical Engineering Society, the American Physiological Society, and the American Society of Pharmacological and Experimental Therapeutics. He has published approximately 90 scientific papers and abstracts and has presented in excess of 350 papers.

Dr. E. D. Haak obtained his B.S. degree in chemical engineering in June 1964 from Purdue University, graduating with honors and as a member of the engineering honorary Tau Beta Phi. He then obtained his M.D. degree in June 1968 from the University of Virginia as a member of the medical honorary Alpha Omega Alpha. From 1968 until 1972 he was at the Johns Hopkins Hospital for a straight medical internship residency and cardiology fellowship. He served 2 years as a Maryland Heart Association research cardiology fellow. From 1972 to date he has been in the USPHS doing clinical research for EPA in Chapel Hill, North Carolina, as the chief of the physiology branch with a joint appointment as an adjunct assistant professor in the University of North Carolina, Division of Cardiology, Department of Medicine.

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